SuperWIMP Cosmology and Collider Physics[a]

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ABSTRACT

Dark matter may be composed of superWIMPs, superweakly-interacting massive particles produced in the late decays of other particles. We focus here on the well-motivated supersymmetric example of gravitino LSPs. Gravitino superWIMPs share several virtues with the well-known case of neutralino dark matter: they are present in the same supersymmetric frameworks (supergravity with R-parity conservation) and naturally have the desired relic density. In contrast to neutralinos, however, gravitino superWIMPs are impossible to detect by conventional dark matter searches, may explain an existing discrepancy in Big Bang nucleosynthesis, predict observable distortions in the cosmic microwave background, and imply spectacular signals at future particle colliders.

1. Introduction

In recent years, there has been tremendous progress in understanding the universe on the largest scales. In particular, the energy density in non-baryonic dark matter is known to be [1]

$$\Omega_{\mathrm{DM}} = 0.23 \pm 0.04 \tag{1}$$

in units of the critical density. At the same time, we have no idea what the microscopic identity of non-baryonic dark matter is. The dark matter problem therefore provides precise, unambiguous evidence for new physics and has motivated new particles such as axions [2,3,4], neutralinos [5,6], Q balls [7], wimpzillas [8], axinos [9], self-interacting dark matter [10], annihilating dark matter [11], Kaluza-Klein dark matter [12,13], branons [14,15], and many others.

Here we review a new class of dark matter candidates: superWIMPs, superweakly-interacting massive particles produced in the late decays of other particles [16,17,18]. SuperWIMPs have several strong motivations:

- They are present in well-motivated frameworks for new physics, including models with supersymmetry (supergravity with R-parity conservation) and extra dimensions (universal extra dimensions with KK-parity conservation).

- Their relic density is naturally in the right range to be dark matter without the need to introduce and fine-tune new energy scales.

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- They can explain an existing anomaly, namely the observed underabundance of ^{7}Li relative to the prediction of standard Big Bang nucleosynthesis.

- They have rich implications for early universe cosmology and imply spectacular signals at the Large Hadron Collider (LHC) and the International Linear Collider (ILC).

2. The Basic Idea

As noted above, superWIMPs exist in theories with supersymmetry and in models with extra dimensions. We concentrate on the supersymmetric scenarios here. Details of the extra dimensional realizations may be found in Refs. [16,17,18].

In the simplest supersymmetric models, supersymmetry is transmitted to standard model superpartners through gravitational interactions, and supersymmetry is broken at a high scale. The mass of the gravitino $\tilde{G}$ is

$$m_{\tilde{G}} = \frac{F}{\sqrt{3}M_*} \ , \tag{2}$$

and the masses of standard model superpartners are

$$\tilde{m} \sim \frac{F}{M_*} \ , \tag{3}$$

where $M_* = (8\pi G_N)^{-1/2} \simeq 2.4 \times 10^{18}$ GeV is the reduced Planck scale and $F \sim (10^{11} \text{ GeV})^2$ is the supersymmetry breaking scale squared. The precise ordering of masses depends on unknown, presumably $\mathcal{O}(1)$, constants in Eq. (3). Most supergravity studies assume that the lightest supersymmetric particle (LSP) is a standard model superpartner, such as the neutralino. In this case, it is well-known that the neutralino naturally freezes out with a relic density that is in the right range to account for dark matter [19].

The gravitino may be the LSP, however [16,17,18,20,21,22,23,24,25,26,27,28]. In supergravity, the gravitino has weak scale mass $M_{\text{weak}} \sim 100$ GeV and couplings suppressed by M_*. The gravitino's extremely weak interactions imply that it is irrelevant during thermal freeze out. The next-to-lightest supersymmetric particle (NLSP) therefore freezes out as usual, and if the NLSP is a slepton, sneutrino, or neutralino, its thermal relic density is again $\Omega_{\text{NLSP}} \sim 0.1$. However, eventually the NLSP decays to its standard model partner and the gravitino. The resulting gravitino relic density is

$$\Omega_{\tilde{G}} = \frac{m_{\tilde{G}}}{m_{\text{NLSP}}}\Omega_{\text{NLSP}} \ . \tag{4}$$

In supergravity, where $m_{\tilde{G}} \sim m_{\text{NLSP}}$, the gravitino therefore inherits a relic density of the right order to be much or all of non-baryonic dark matter. The superWIMP gravitino scenario preserves the prime virtue of WIMPs, namely that they give the desired amount

of dark matter without relying on the introduction of new, fine-tuned energy scales.[b]

Because superWIMP gravitinos interact only gravitationally, with couplings suppressed by M_*, they are impossible to detect in conventional direct and indirect dark matter search experiments. At the same time, the extraordinarily weak couplings of superWIMPs imply other testable signals. The NLSP is a weak-scale particle decaying gravitationally and so has a natural lifetime of

$$\frac{M_*^2}{M_{\text{weak}}^3} \sim 10^4 - 10^8 \text{ s} . \tag{5}$$

This decay time, outlandishly long by particle physics standards, implies testable cosmological signals, as well as novel signatures at colliders.

3. Cosmology

The most sensitive probes of late decays with lifetimes in the range given in Eq. (5) are from Big Bang nucleosynthesis (BBN) and the Planckian spectrum of the cosmic microwave background (CMB). The impact of late decays to gravitinos on BBN and the CMB are determined by only two parameters: the lifetime of NLSP decays and the energy released in these decays. The energy released is quickly thermalized, and so the cosmological signals are insensitive to the details of the energy spectrum and are determined essentially only by the total energy released.

The width for the decay of a slepton to a gravitino is

$$\Gamma(\tilde{l} \to l\tilde{G}) = \frac{1}{48\pi M_*^2} \frac{m_{\tilde{l}}^5}{m_{\tilde{G}}^2} \left[1 - \frac{m_{\tilde{G}}^2}{m_{\tilde{l}}^2} \right]^4 , \tag{6}$$

assuming the lepton mass is negligible. (Similar expressions hold for the decays of a neutralino NLSP.) This decay width depends on only the slepton mass, the gravitino mass, and the Planck mass. In many supersymmetric decays, dynamics brings a dependence on many supersymmetry parameters. In contrast, as decays to the gravitino are gravitational, dynamics is determined by masses, and so no additional parameters enter. In particular, there is no dependence on left-right mixing or flavor mixing in the slepton sector. For $m_{\tilde{G}}/m_{\tilde{l}} \approx 1$, the slepton decay lifetime is

$$\tau(\tilde{l} \to l\tilde{G}) \simeq 3.6 \times 10^8 \text{ s} \left[\frac{100 \text{ GeV}}{m_{\tilde{l}} - m_{\tilde{G}}} \right]^4 \left[\frac{m_{\tilde{G}}}{\text{TeV}} \right] . \tag{7}$$

This expression is valid only when the gravitino and slepton are nearly degenerate, but it is a useful guide and verifies the rough estimate of Eq. (5).

The energy release is conveniently expressed in terms of

$$\xi_{\text{EM}} \equiv \epsilon_{\text{EM}} B_{\text{EM}} Y_{\text{NLSP}} \tag{8}$$

for electromagnetic energy, with a similar expression for hadronic energy. Here ϵ_{EM} is the initial EM energy released in NLSP decay, and B_{EM} is the branching fraction of NLSP decay into EM components. $Y_{\text{NLSP}} \equiv n_{\text{NLSP}}/n_\gamma$ is the NLSP number density just before NLSP decay, normalized to the background photon number density $n_\gamma = 2\zeta(3)T^3/\pi^2$. It can be expressed in terms of the superWIMP abundance:

$$Y_{\text{NLSP}} \simeq 3.0 \times 10^{-12} \left[\frac{\text{TeV}}{m_{\tilde{G}}} \right] \left[\frac{\Omega_{\tilde{G}}}{0.23} \right] \ . \tag{9}$$

Once an NLSP candidate is specified, and assuming superWIMPs make up all of the dark matter, with $\Omega_{\tilde{G}} = \Omega_{\text{DM}} = 0.23$, the early universe signals are completely determined by only two parameters: $m_{\tilde{G}}$ and m_{NLSP}.

3.1. BBN Electromagnetic Constraints

BBN predicts primordial light element abundances in terms of one free parameter, the baryon-to-photon ratio $\eta \equiv n_B/n_\gamma$. In the past, the fact that the observed D, ^{4}He, ^{3}He, and ^{7}Li abundances could be accommodated by a single choice of η was a well-known triumph of standard Big Bang cosmology.

More recently, BBN baryometry has been supplemented by CMB data, which alone yields $\eta_{10} = \eta/10^{-10} = 6.1 \pm 0.4$ [1]. This value agrees precisely with the value of η determined by D, considered by many to be the most reliable BBN baryometer. However, it highlights slight inconsistencies in the BBN data. Most striking is the case of ^{7}Li. For $\eta_{10} = 6.0 \pm 0.5$, the value favored by the combined D and CMB observations, the standard BBN prediction is [41]

$$^7\text{Li/H} \ = \ 4.7^{+0.9}_{-0.8} \times 10^{-10} \tag{10}$$

at 95% CL. This contrasts with observations. Three independent studies find

$$^7\text{Li/H} \ = \ 1.5^{+0.9}_{-0.5} \times 10^{-10} \quad (95\% \text{ CL}) \text{ [42]} \tag{11}$$

$$^7\text{Li/H} \ = \ 1.72^{+0.28}_{-0.22} \times 10^{-10} \ (1\sigma + \text{sys}) \text{ [43]} \tag{12}$$

$$^7\text{Li/H} \ = \ 1.23^{+0.68}_{-0.32} \times 10^{-10} \ (\text{stat} + \text{sys}, 95\% \text{ CL}) \text{ [44]} \ , \tag{13}$$

where depletion effects have been estimated and included in the last value. Within the published uncertainties, the observations are consistent with each other but inconsistent with the theoretical prediction of Eq. (10), with central values lower than predicted by a factor of 3 to 4. ^{7}Li may be depleted from its primordial value by astrophysical effects, for example, by rotational mixing in stars that brings Lithium to the core where it may be burned [45,46], but it is controversial whether this effect is large enough to reconcile observations with the BBN prediction [44].

We now consider the effects of NLSP decays to gravitinos. For WIMP NLSPs, that is, sleptons, sneutrinos, and neutralinos, the energy released is dominantly deposited in electromagnetic cascades. For the decay times of Eq. (5), mesons decay before they interact hadronically. The impact of EM energy on the light element abundances has been
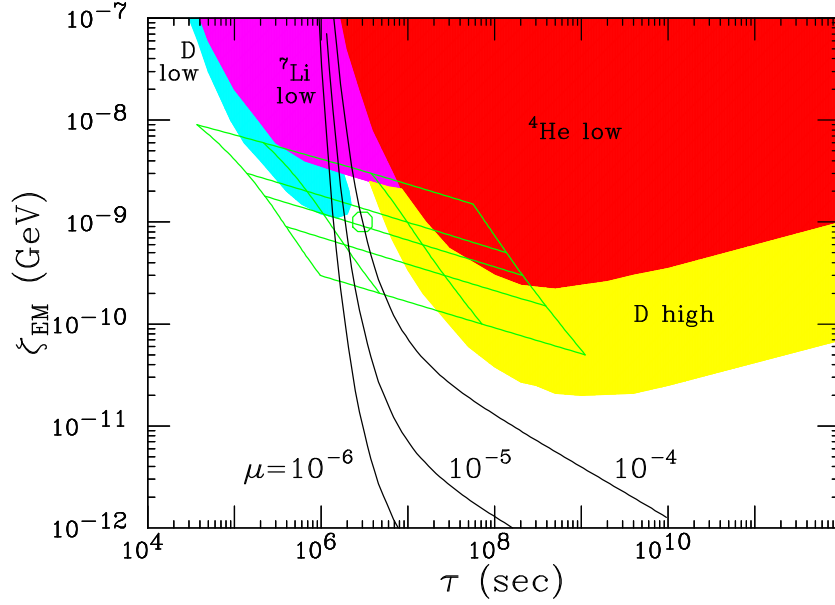
Figure 1: Predicted and excluded regions of the (τ, ζ_{EM}) plane in the superWIMP dark matter scenario, where τ is the lifetime for $\tilde{l} \to l\tilde{G}$, and ζ_{EM} is the normalized electromagnetic energy release. The grid gives predicted values for $m_{\tilde{G}} = 100$ GeV $- 3$ TeV (top to bottom) and $\Delta m \equiv m_{\tilde{l}} - m_{\tilde{G}} = 600$ GeV $- 100$ GeV (left to right), assuming $\Omega_{\tilde{G}} = 0.23$. BBN constraints exclude the shaded regions; the circle indicates the best fit region where ^{7}Li is reduced to observed levels without upsetting other light element abundances. Contours of CMB μ distortions indicate the current bound ($\mu < 0.9 \times 10^{-4}$) and the expected future sensitivity of DIMES ($\mu \sim 10^{-6}$). From Ref. [17].

studied in Refs. [47,48,49,50]. The results of Ref. [50] are given in Fig. 1. The shaded regions are excluded because they distort the light element abundances too much. The predictions of the superWIMP scenario for a stau NLSP with $m_{\tilde{G}}$ and m_{NLSP} varying over weak scale parameters are given in Fig. 1 by the grid.

We find that the BBN constraint excludes some weak scale parameters. However, much of the weak scale parameter space remains viable. Note also that, given the ^{7}Li discrepancy, the best fit is not achieved at $\xi_{EM} = 0$, but rather for $\tau \sim 3 \times 10^6$ s and $\xi_{EM} \sim 10^{-9}$ GeV, where ^{7}Li is destroyed by late decays without changing the other relic abundances. This point is marked by the circle in Fig. 1. The energy release predicted in the superWIMP scenario naturally includes this region. The ^{7}Li anomaly is naturally resolved in the superWIMP scenario by a stau NLSP with $m_{NLSP} \sim 700$ GeV and $m_{\tilde{G}} \sim 500$ GeV.

3.2. BBN Hadronic Constraints

Hadronic energy release is also constrained by BBN [51,52,53,54,55,56,57]. In fact, constraints on hadronic energy release are so severe that even subdominant contributions to hadronic energy may provide stringent constraints.

Slepton and sneutrino decays contribute to hadronic energy through the higher order

processes

$$
\begin{aligned}
\tilde{l} &\rightarrow lZ\tilde{G} \ , \ \nu W\tilde{G} \\
\tilde{\nu} &\rightarrow \nu Z\tilde{G} \ , \ lW\tilde{G} \ ,
\end{aligned}
\tag{14}
$$

when the Z or W decays hadronically. These three-body decays may be kinematically suppressed when $m_{\tilde{l},\tilde{\nu}} - m_{\tilde{G}} < m_W, m_Z$, but even in this case, four-body decays, such as $\tilde{l} \rightarrow l\gamma^*\tilde{G} \rightarrow lq\bar{q}\tilde{G}$, contribute to hadronic cascades and may be important. The branching fractions for these decays have been calculated in Refs. [23,24]. The end result is that these constraints are stringent and important, as they exclude regions of parameter space that would otherwise be allowed. At the same time, much of the parameter space in the case of slepton and sneutrino NLSPs remains viable. For details, see Refs. [23,24,58].

In contrast to the case of slepton and sneutrino NLSPs, the neutralino NLSP possibility is very severely constrained by bounds on hadronic energy release. This is because neutralinos contribute to hadronic energy even through two-body decays

$$
\chi \rightarrow Z\tilde{G}, \ h\tilde{G} \ ,
\tag{15}
$$

followed by $Z, h \rightarrow q\bar{q}$. The resulting hadronic cascades destroy BBN successes, and exclude this scenario unless such decays are highly suppressed. Kinematic suppression is not viable, however — if $m_\chi - m_{\tilde{G}} < m_Z$, the decay $\chi \rightarrow \gamma\tilde{G}$ takes place so late that it violates bounds on EM cascades. Neutralino NLSPs are therefore allowed only when the two-body decays to Z and h bosons are suppressed dynamically, as when the neutralino is photino-like, a possibility that is not well-motivated by high energy frameworks.

3.3. CMB Constraints

The injection of electromagnetic energy may also distort the frequency dependence of the CMB black body radiation. For the decay times of interest, with redshifts $z \sim 10^5$ to 10^7, the resulting photons interact efficiently through $\gamma e^- \rightarrow \gamma e^-$ and $eX \rightarrow eX\gamma$, where X is an ion, but photon number is conserved, since double Compton scattering $\gamma e^- \rightarrow \gamma\gamma e^-$ is inefficient. The spectrum therefore relaxes to statistical but not thermodynamic equilibrium, resulting in a Bose-Einstein distribution function

$$
f_\gamma(E) = \frac{1}{e^{E/(kT)+\mu} - 1} \ ,
\tag{16}
$$

with chemical potential $\mu \neq 0$.

In Fig. 1 we show contours of chemical potential μ, as determined by updating the analysis of Ref. [59]. The current bound is $\mu < 9 \times 10^{-5}$ [60,61]. We see that, although there are at present no indications of deviations from black body, current limits are already sensitive to the superWIMP scenario, and are even beginning to probe regions favored by the BBN considerations described above. In the future, the Diffuse Microwave Emission Survey (DIMES) may improve sensitivities to $\mu \approx 2 \times 10^{-6}$ [62]. DIMES will

therefore probe further into superWIMP parameter space, and will effectively probe all of the favored region where the ^{7}Li underabundance is explained by decays to superWIMPs.

4. Colliders

As noted in Eq. (5), the next-to-lightest supersymmetric particle (NLSP) decays to the gravitino with lifetime naturally in the range $10^4 - 10^8$ s. However, as described above, cosmological constraints exclude lifetimes at the upper end of this range and disfavor neutralinos as NLSPs, leaving charged sleptons with lifetimes below a year as the natural NLSP candidates. The gravitino superWIMP scenario therefore implies that the signal of supersymmetry at colliders will be meta-stable sleptons with lifetimes of a month or a year. This is a spectacular signal that will not escape notice at the LHC [63,64,65,66]. In addition, given the long lifetime, it suggests that decays to gravitinos may be observed by trapping slepton NLSPs in water tanks placed outside collider detectors and draining these tanks periodically to underground reservoirs where slepton decays may be observed in quiet environments.

This possibility has been considered in Refs. [67,68]. In Ref. [68], we have explored the prospects for trapping sleptons at the LHC by optimizing the water trap shape and placement and considering a variety of sizes. The results of Monte-Calo simulations using the ISASUSY package [69] are displayed in Fig. 2. The number that may be trapped is highly model-dependent. For minimal supergravity with $m_0 = 0$, we find that as many as 10^4 staus may be stopped in a 10 kton trap when the sleptons have mass around 100 GeV. This is as light as is allowed by current bounds. For a less optimistic scenario with 219 GeV staus, hundreds and tens of sleptons may be caught each year in 10 kton and 1 kton traps, respectively.

The LHC results may be improved significantly if long-lived NLSP sleptons are kinematically accessible at the ILC. For the identical case with 219 GeV sleptons discussed above, $\mathcal{O}(1000)$ sleptons may be trapped each year in a 10 kton trap. If only the NLSP is accessible, this result may be achieved by tuning the beam energy so that produced NLSPs barely escape the ILC detector. The ability to prepare initial states with well-known energies and the flexibility to tune this energy are well-known advantages of the ILC. Here, these features are exploited in a qualitatively new way to produce slow sleptons that are easily captured.

If there are additional superpartner states accessible at the ILC, even tuning the beam energy is not necessary. The cascade decays of other superpartner states produce a broad distribution of slepton energies, and so for a broad range of beam energies, some sleptons will be captured in the trap. We have noted also that, by considering the slightly more general possibility of placing lead or other dense material between the ILC detector and the slepton trap, an order of magnitude enhancement may be possible, allowing up to $\mathcal{O}(10^4)$ sleptons to be trapped per ILC year.

The analysis here is valid with minor revisions for traps composed of any material. For concreteness we have considered traps composed of water tanks, with the expectation that sleptons caught in water will be easily concentrated and/or moved to quiet environments.
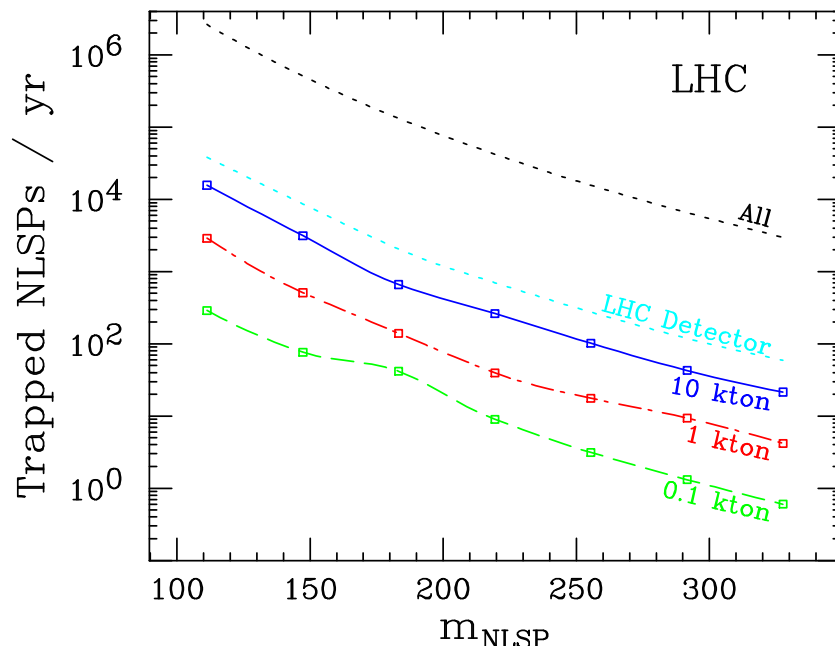
Figure 2: The number of sleptons trapped per year at the LHC in water tanks of size 10 kton (solid), 1 kton (dot-dashed), and 0.1 kton (dashed). The total number of sleptons produced is also shown (upper dotted), along with the number of sleptons trapped in the LHC detector (lower dotted). These results assume luminosity 100 fb^{-1}/ yr and minimal supergravity models with $M_{1/2} = 300, 400, \ldots, 900$ GeV, $m_0 = 0$, $A_0 = 0$, $\tan\beta = 10$, and $\mu > 0$. From Ref. [68].

Other possibilities, such as that considered in Ref. [67], are, however, well worth exploring.

5. Conclusions

Although the implications of supergravity for cosmology and particle physics have been considered in great detail for decades, most work has been centered on scenarios in which the LSP is a standard model superpartner. Here we have explored the gravitino LSP scenario. Recent work has found significant cosmological motivations for this possibility, as the gravitino may explain dark matter, and the scenario may resolve current difficulties in Big Bang nucleosynthesis.

Despite the extremely weak couplings of superWIMPs, this scenario has striking implications for cosmology and particle physics. In cosmology, the scenario predicts possible μ distortions in the CMB spectrum at a level that will be probed by the planned DIMES mission. Such distortions would provide significant corroborating evidence for superWIMP dark matter.

The superWIMP scenario also implies long-lived charged particles, which will provide a spectacular signal at colliders. As discussed above, such particles may be trapped and their decays studied in detail. There are many significant implications of such studies. In the case of supersymmetry and gravitino superWIMPs, these implications have been considered in detail in Refs. [21,25]. Briefly, simply by counting the number of slepton decays as a function of time, the slepton lifetime may be determined with high accuracy.
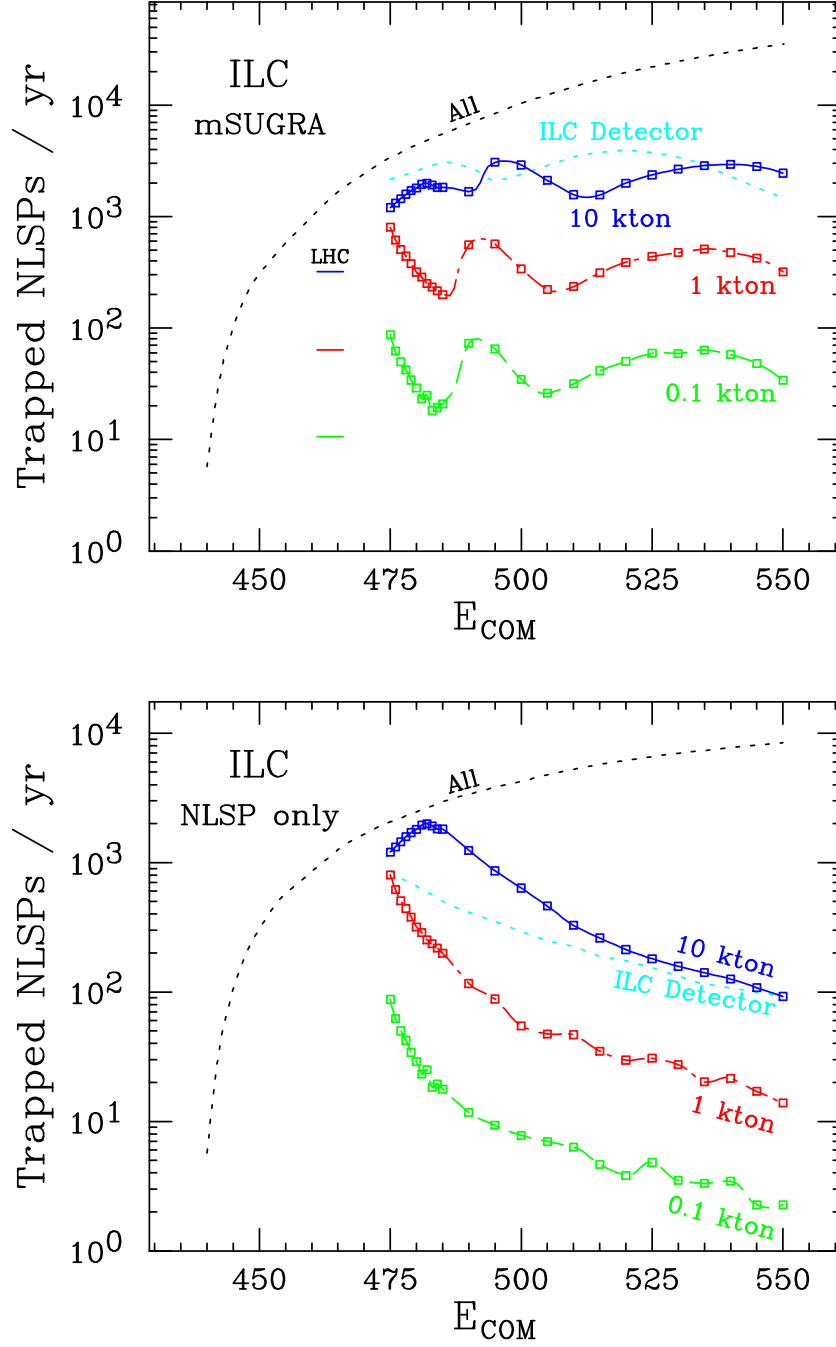
Figure 3: The number of sleptons trapped per year at the ILC in 10 kton (solid), 1 kton (dot-dashed), and 0.1 kton (dashed) water traps. The total number of sleptons produced is also shown (upper dotted) along with the number of sleptons trapped in the ILC detector (lower dotted). The trap shape and placement have been optimized and we assume luminosity 300 fb^{-1}/yr. In the top figure, the underlying model is minimal supergravity with $M_{1/2} = 600$ GeV, $m_0 = 0$, $A_0 = 0$, $\tan \beta = 10$, and $\mu > 0$. The LHC results for this model are indicated. In the bottom figure, the only accessible superpartner is a 219 GeV NLSP stau. From Ref. [68].

Given thousands of sleptons, we expect a determination at the few percent level. The slepton decay width of Eq. (6) is a simple function of the slepton and gravitino masses, and the slepton mass will be constrained by analysis of the collider event kinematics. A measurement of the slepton width therefore implies a high precision measurement of the gravitino mass and, through Eq. (2), the supersymmetry breaking scale F. Such measurements will provide precision determinations of the relic density of superWIMP gravitino dark matter, the contribution of supersymmetry breaking to vacuum energy, and the opportunity for laboratory studies of late decay phenomena relevant for Big Bang nucleosynthesis and the cosmic microwave background.

The gravitino mass may also be determined, although not necessarily on an event-by-event basis, by measuring the energy of slepton decay products. This provides a consistency check. Alternatively, these two methods, when combined, determine not only $m_{\tilde{G}}$, but also the Planck mass M_*. This then provides a precision measurement of Newton's constant on unprecedentedly small scales, and the opportunity for a quantitative test of supergravity relations.

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